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JOVIAN MAGNETOSPHERIC PROCESSES

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ABSTRACT

Jupiter's rotational energy (6×10^{34} J) powers a large number of processes such as auroral UV emission, radio waves, and charged particle energization. We describe how the rotational energy may be dissipated by injection of plasma, magnetic pumping and field aligned electric fields. In addition, we describe energization by radial diffusion and plasma wave absorption. We also describe the generation of Alfven waves by the moon Io and their relation to the emission of the Jovian decametric (DAM) radio waves.

INTRODUCTION

Jupiter's huge magnetosphere may be of special interest to astrophysicists for several reasons.

1. Its structure is determined by the rapid rotation of Jupiter and strong internal plasma sources (Jovian ionosphere and the moon Io).
2. It produces very energetic charged particles (energies in excess of several 10's of MeV).
3. It is a strong source of radio waves.
4. It also emits UV and X-rays at levels which suggest non-thermal processes.

Jupiter has been likened to a pulsar[1] and to a binary star system.[2] Even though these analogies may seem somewhat artificial, we believe that processes occurring in the Jovian magnetosphere are of astrophysical interest. In this paper we will discuss the rotation of the Jovian magnetosphere and the energization of plasma by the rotation. The existence of MeV electrons and ions, however, requires additional energization mechanisms which may involve betatron and Fermi acceleration as well as magnetic pumping. We also discuss the interaction of Io with the corotating plasma which controls much of the Jovian radio emission. Finally, we discuss particle precipitation by wave-particle interactions and its relation to the auroral UV emissions.

Our knowledge of the Jovian magnetosphere has made great leaps following the two Pioneer (in the early 1970's) and the two Voyager fly-bys in 1979. Nevertheless, most of the Jovian magnetosphere has not been explored. For example, the high latitude region of the inner magnetosphere and the dusk to midnight region of the magnetotail have not been traversed by any of the spacecraft. Satellites have traversed the Io torus only at a few longitudes and we are still not certain whether it is longitudinally symmetric or not. They have flown close to Io only once and not through the region which carries the Io-driven Birkeland currents. We still have no measurements of plasma parameters in the source region of

(NASA-CR-180039) JOVIAN MAGNETOSPHERIC PROCESSES, APPENDIX 18 (Iowa Univ.) 16 p

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DAM. Clearly, many of our ideas about the Jovian magnetosphere are still in the stage of enlightened speculation.

MAGNETOSPHERIC ROTATION

There are important differences between pulsar magnetospheres and the Jovian magnetosphere which make a comparison of limited value. In the local stress balance equation

$$\rho(d\vec{v}/dt - \vec{g}) + \nabla \cdot p = \vec{j} \times \vec{B} + \rho_e \vec{E} = \left(\frac{\nabla \times \vec{B}}{\mu_o}\right) \times \vec{B} + \varepsilon_o(\nabla \cdot \vec{E})\vec{E} \qquad (1)$$

the ratio R_1 of the two terms on the right-hand side is quite different for the two cases. Reducing we have:

$$R_1 = \frac{\mu_o \varepsilon_0 (\nabla \cdot \vec{E})\vec{E}}{(\nabla \times \vec{B}) \times B} \approx \frac{\Omega^2 r^2}{c^2} \qquad (2)$$

(where $\vec{E} + (\vec{\Omega} \times \vec{r}) \times \vec{B} = 0$, has been assumed). R_1 is extremely small at Jupiter whereas it is comparable to 1 for pulsars. Thus for Jupiter we can neglect the charge density. In addition, we can safely neglect the displacement current $\varepsilon_o\ \partial\vec{E}/\partial t$ as compared to the conduction current. For pulsar magnetospheres the inertia terms on the left-hand side are often small, at Jupiter they are very important. The ratio of inertia current to the convection current $\rho_e \Omega r$ is

$$R_2 = \frac{\rho(d\vec{v}/dt - \vec{g}) + \nabla p}{B\ \varepsilon_o(\nabla \cdot E)E\ \Omega r} \approx \frac{\rho}{\varepsilon_o B^2}\left(1 - \frac{g}{\Omega^2 r} - \frac{kT}{m\Omega^2 r^2}\right) \quad . \qquad (3)$$

The ratio $\rho/\varepsilon_o B^2$ is equal to $c^2/v_A{}^2$, where v_A is the Alfvén speed. In the outer magnetosphere of Jupiter, the Alfvén speed is on the order of a few 100 km/s. Even near the surface where the magnetic field is large the ratio $c^2/v_A{}^2$ is greater than 10^{+2}. Thus the inertia current is most important at Jupiter.

If the field lines are equipotentials (i.e., if the parallel electric field $E_\parallel$ equals 0) the angular rotation rate Ω is a constant along field lines and for an azimuthally symmetric magnetic field only a function of L, the usual L-shell parameter. The total rotational energy of Jupiter is 6×10^{34} J and is believed to be the dominant energy source for processes such as enforcing (partial) corotation of plasma produced within the magnetosphere, plasma heating, auroral emissions, production of high energy charged particles and the system of radial transport in the outer magnetosphere.[1]

The simplest way of tapping the rotational energy involves the magnetic-field-aligned (Birkeland) current system shown in Figure 1

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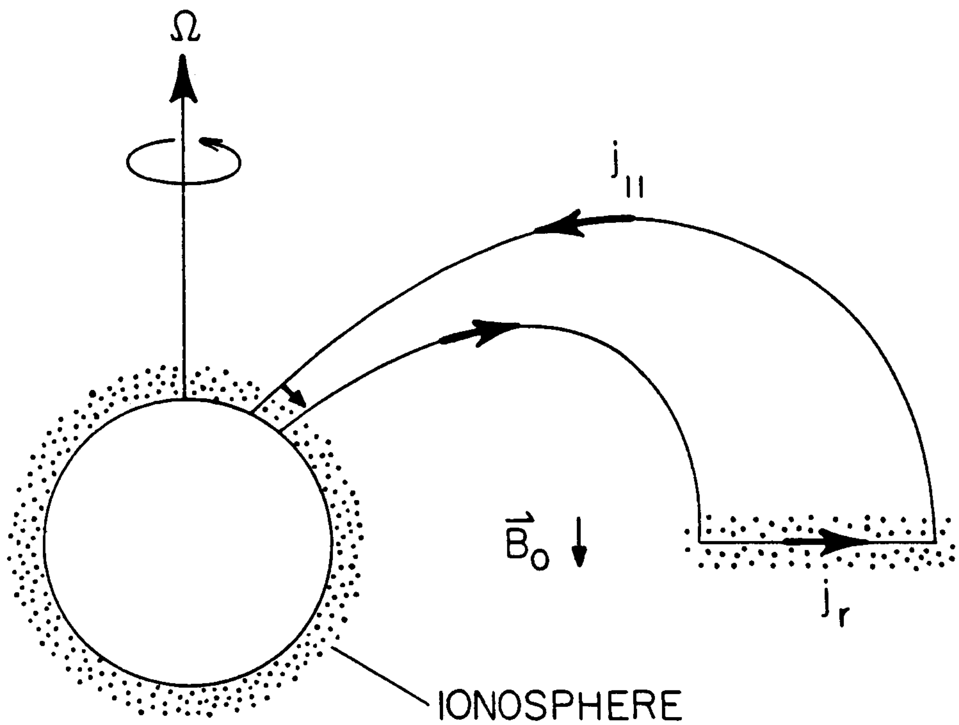

Fig. 1. The current system that transmits torque from Jupiter's ionosphere to the plasma in the equatorial region (e.g., the Io torus). The equatorial current spins up the plasma whereas the ionospheric current tends to spin down the ionosphere. Note that field aligned Birkeland currents must flow. These may become unstable to double-layer formation or other mechanisms supporting a parallel electric field.

which exerts the necessary torque to produce and maintain the corotation of plasma produced in, or injected into, the magnetosphere. Note that the torque in the ionosphere tends to spin down the ionosphere which is coupled to the neutral atmosphere by ion-neutral collisions. Regardless of where the new plasma particles are produced they gain an energy of about twice the local corotation energy $W_c = m\,\Omega^2 r^2/2$. If they are produced in the equatorial plane the corotation electric field increases their gyroenergy by $W_\perp = W_c + W_o - 2\sqrt{W_o W_c}$ where W_o is the kinetic energy of the neutral which is ionized ($W_o = mM_J G/r \ll W_c$ beyond about 2 R_J). In addition, they gain the corotational drift energy ($= W_c$). If the ions originate in the ionosphere and are pulled up by hot photoelectrons, the centrifugal sling-shot effect[3] increases their energy by $W_\parallel = W_c - mM_J G/r$ in addition to the corotational drift energy. For intermediate source positions the energy gain is distributed between parallel and perpendicular energy. For an injection rate of S (ions/s) the rate of energy extraction is thus 2 S W_c.

When the injected plasma is transported outward, even more investment of rotational energy is needed to maintain (partial) corotation.[4,5,6,7] The total power extracted is given by Hill et

$$P = S \left[\frac{1}{2} \Omega_J^2 (L_s R_J)^2 - M_J G/(L_s R_J) + \int_{L_s R_J}^{\infty} \omega^2 r dr\right] \quad (4)$$

where L_s (usually 6 for injection from Io) is the L value of the field line on which the injection occurs. The rotation rate of the plasma in the magnetosphere, ω, may be different from the planetary rotation rate Ω. The first two terms represent the energy gained in the source and the third represents the energy gained as the ions are transported outward. Hill[8] has shown that corotation is maintained up to a critical distance

$$r_c/R_J = (\pi \ \Sigma \ B_J^2 \ R_J^2/S)^{1/4} \quad (5)$$

where Σ is the ionospheric Pedersen conductance ($\Sigma \sim 0.1$ mho). For an Io injection strength of $S \sim 1700$ kg/s this yields $r_c = 20\ R_J$ consistent with observations.[9] For these nominal values, the total rotational energy extracted is about 5×10^{13} W which is somewhat less than the power needed to maintain the auroral UV emission (10^{14} W).

The centrifugal force necessary to maintain the plasma in (partial) corotation is provided for by the $\vec{j} \times \vec{B}$ term in equation (1). The centrifugal current is in the azimuthal direction and corresponds to a slight difference in azimuthal drifts of the ions and electrons. It distorts the magnetic field into a disc-like configuration. Various theoretical models for this distortion have been discussed and are reviewed by Vasyliunas.[10]

The mode of outward transport is not clear. Kennel and Coroniti[11] have suggested that an axially symmetric stellar-wind-like transport occurs. The average radial velocity is non-zero. However, this does not really apply to Jupiter because a steady wind would require open field lines which do not seem to exist in the inner and middle magnetosphere. Their solution also lacks the day-night asymmetry imposed by the solar wind. Thus Hill et al.[12] have proposed that the wind only exists on the nightside where it is not constrained by the solar wind. Vasyliunas[10] has suggested that a neutral line exists in the nightside magnetotail beyond which the field lines are open and the wind solution can apply (Figure 2). The observations of Krimigis et al.[13] seem to confirm this picture.

The transport in the closed field regions (inner and middle magnetosphere) must occur by diffusion, i.e., a correlation between density and radial plasma flow. In this case the average radial velocity $\langle v_r \rangle = \langle E_\phi \rangle / B$ is zero, but $\langle \rho v_r \rangle$, the average radial mass flux is not zero. The mechanism responsible for diffusing low energy plasma may be different from that responsible for diffusing

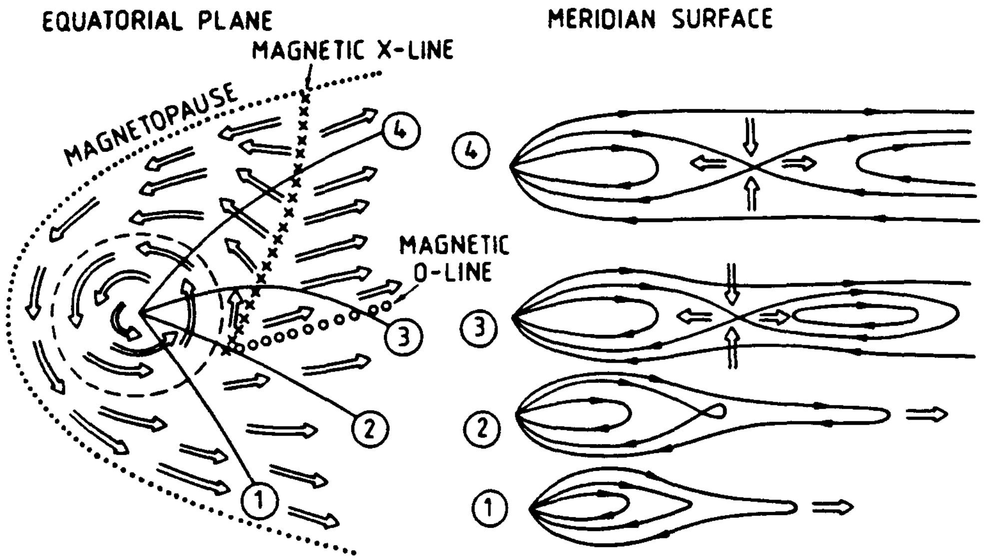

Fig. 2. A sketch of the equatorial plasma flow (left) and associated magnetic fields (right) according to Vasyliunas.[10]

high energy particles (see below). Siscoe and Summers[14] have pointed out that the inward plasma density gradient on the outer edge of the plasma torus would be unstable to the centrifugal drift instability. This instability is similar to the Rayleigh-Taylor instability. In a rotating plasma the effective force is outwards beyond synchronous orbit. Thus an inward density gradient corresponds to a heavy fluid on top of a light fluid which is an unstable situation with an excess of free energy. The flute mode ($k_\parallel \simeq 0$) would cause radial transport of plasma by interchange of magnetic flux tubes. The size of the flux tubes is not known, but a likely size seems to be 1 to 2 R_J.[14]

Independent of the mechanism of radial transport, a time-averaged radial outward transport requires a radial current to impart the torque on the plasma necessary for maintaining (partial) corotation. This radial current distorts the magnetic field into a spiral configuration. This has, indeed, been observed. The observed azimuthal magnetic field is consistent with an outward mass transport of 10^3 kg/s.[10,15]

ENERGIZATION MECHANISMS

The energies produced directly by the rotation of Jupiter are of the order of (60 eV) $(r/6\ R_J)^2\ (m/m_p)$ and thus considerably smaller than the MeV energies of some electrons and ions observed in the magnetosphere. The acceleration mechanisms which can produce such large energies can be classified according to the degree to which they violate the three adiabatic invariants. According to Hill, Dessler, and Goertz[1] processes which violate only the third adiabatic invariant (related to the magnetic flux enclosed by a drift orbit) are called "adiabatic". Those which violate one or both of the other two (related to the magnetic moment of a particle and the bounce integral) are called "nonadiabatic."

A. Adiabatic Processes

The most widely discussed mechanism for magnetospheric particle acceleration is due to adiabatic compression. As the particles are transported across magnetic flux shells conservation of the first adiabatic invariant (magnetic moment) implies a betatron acceleration ($E_\perp \propto B$). Conservation of the second invariant (bounce integral) implies a Fermi acceleration ($E_\parallel \propto \ell^{-2}$, with ℓ being the length of the field line between mirror points). For a dipole field $E_\perp \propto r^{-3}$ and $E_\parallel \propto r^{-2}$. Thus, as particles are transported inward their energy increases and the distribution tends toward a pancake pitch-angle distribution with $\langle E_\perp \rangle > \langle E_\parallel \rangle$. If pitch-angle scattering which violates the adiabatic invariants would occur without loss of particles into the atmosphere, the distribution function would remain isotropic and the energy would change as $E \propto r^{-8/3} \propto V^{-2/3}$ where V is the volume of a flux tube transported inward or outward. This would be the analogy to the adiabatic compression of an ideal monoatomic gas.

Even though radial transport occurs and this adiabatic acceleration takes place undoubtedly, it alone is not sufficient to explain the presence of MeV particles at say L = 20. For example, solar wind protons enter the magnetosphere with an energy of a few keV and would have an energy of only a few 100 keV at L = 20. Solar wind electrons would be even less energetic. Newly created ions at 100 R_J would have an energy of less than $17(m/m_p)$ keV and would not be energized to several tens of MeV by the time they reach L = 20. In addition, diffusion (or radial transport) is a slow process with a typical time scale of years.[1] The emission rate of energetic particles into interplanetary space requires that they are resupplied with a time scale of a few rotation periods (a few 10's of hrs).[16] Thus faster and more powerful mechanisms are required to produce energetic particles in the outer magnetosphere. Once they are produced they may gain additional energy by inward diffusion.

We note that only inward transport would give rise to an energy increase by the adiabatic mechanism. Thus the source for the particles must be in the outer magnetosphere. If the source were close to Jupiter (say in the Io torus) outward transport would adiabatically decrease the particle's energy.

B. Quasi-Adiabatic Processes

Nishida[17] and Sentman, Van Allen and Goertz[18] have proposed a "recirculation model" which overcomes the difficulty posed by the adiabatic deceleration of outward moving particles. They point out that in the inner magnetosphere (say at L < 10) the distribution

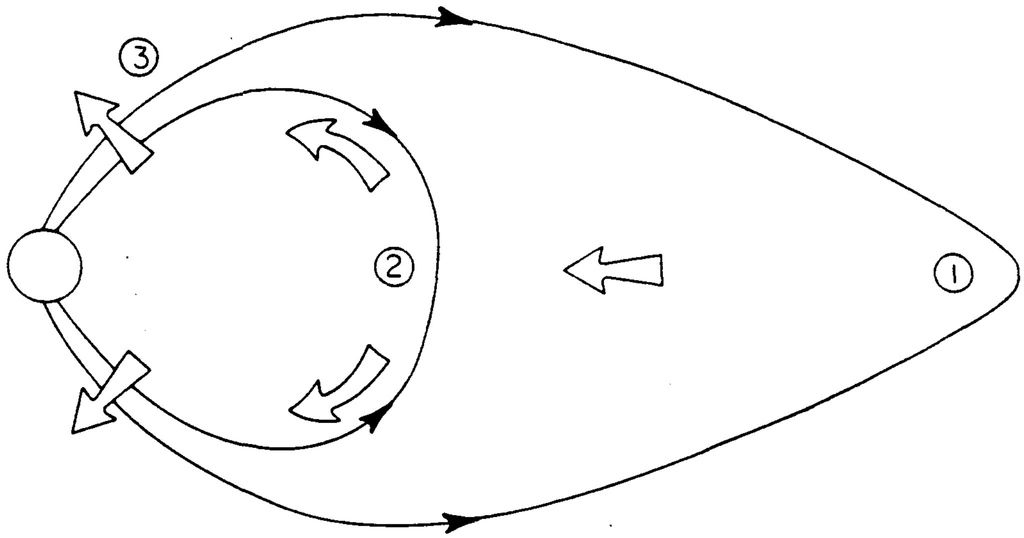

Fig. 3. A sketch of the "recirculation model". The arrows indicate the direction of the diffusive transport as described in the text.

function of inward diffusing particles (moving from point 1 to point 2 in Figure 3) will be anisotropic enough to generate electromagnetic electron and ion-cyclotron waves by an instability (see below). These waves will cause a pitch-angle scattering, thereby allowing some particles to mirror at low altitudes (point 3) where they are subject to meridional diffusion as a result of low frequency waves violating only the second adiabatic invariant. This diffusion transports particles toward large values of L because the source for these low altitude mirroring particles is at low L values. In this process the total energy of the particle is conserved. The net result is that the particles return to point 1 with field aligned energies comparable to the energy gained by adiabatic diffusion from point 1 to point 2. Pitch-angle scattering of this distribution will then produce a high energy nearly isotropic distribution at point 2 and the process can start over again. Particles can then, in principle, repeat the cycle many times and gain high energies. However, Sentman et al.[18] point out that the combination of several diffusive processes makes this recirculation a slow process.

The other quasi-adiabatic process was investigated by Goertz[19] and Borovsky et al.[20] They suggest that due to the day-night asymmetry of the magnetosphere, particles corotating from day to night and back will encounter a varying magnetic field strength. As the particles drift from noon to midnight they experience an adiabatic betatron and Fermi deceleration and the distribution will become more dumbbell-shaped (i.e., field aligned). Without pitch-angle scattering this energy loss would be reversible as the particles drift from midnight to noon. However, if non-adiabatic pitch-angle scattering (without change of energy) would occur some of the energy gained during the midnight to noon half of the orbit would be stored in the parallel component at noon and escape the deceleration during the noon to midnight half of the orbit. This mechanism is the analog of the magnetic pumping mechanism of Alfvén.[21] In the most advantageous case (pitch-angle scattering time = rotation period) the average energy can increase by a factor of 2 each cycle, i.e., the energization time would be equal to the rotation period (10 hrs). This mechanism may thus account for the energization of particles in the outer magnetosphere. However, some observations[16] require acceleration processes which occur on time scales much less than 10 hrs.

C. Non-Adiabatic Processes

Non-adiabatic processes violate all three adiabatic invariants. Three processes have been suggested to be operative in the Jovian magnetosphere: magnetic reconnection (or merging), parallel electric fields and plasma wave heating.

The magnetic field topology in the magnetodisc is favorable to the occurrence of sporadic and/or steady state reconnection. For steady state merging the average energy gain is equal to the magnetic energy density outside the current sheet divided by the density in the current sheet.[1] For $B = 10$ nT and $n = 0.1$ cm^{-3} one obtains an energy gain of $(B^2/\mu_0 n) \sim 5$ keV. Thus steady state merging cannot account for MeV particles. Sporadic (time-dependent) merging may produce higher energies as observed in the earth's magnetotail.[22] However, the theoretical understanding and modelling of particle acceleration in sporadic merging is not well understood.

As shown in Figure 1, we expect field aligned currents to be present in the Jovian magnetosphere, even though the magnitude and location of the field aligned current density and currents is not known. Whenever the field aligned current density exceeds a critical value (which is not well established theoretically) a parallel electric field occurs. The field aligned potential drop ($\phi_\parallel = -\int E_\parallel ds$) may be a significant fraction of the total EMF driving the current. The electric potential for corotation in the equatorial plane is $\phi = \Omega_J B_J R_J{}^2/L \approx 376$ MV/L. If only a fraction of this would appear along the field lines a powerful linear accelerator could become active and cause the appearance of MeV particles. The potential drop between field lines in the equatorial plane would then be different from that in the ionosphere. In other words, the outer magnetosphere would slip relative to the ionosphere. Thus this model is sometimes called the "slippery clutch" model. This mechanism must not be confused with the partial corotation described above where the entire flux tube slips through the neutral atmosphere. The theory of the "slippery clutch" model has not been formulated in any detail.

Heating of particles by absorption of plasma waves is potentially very significant. For example, ion cyclotron waves, driven by field aligned currents, are believed to be responsible for the acceleration of O^+ ions in the earth's magnetosphere.[23] However, the question of the ultimate power source is not answered by this model. Somehow the waves must be maintained at a sufficient level to provide efficient and fast heating. Recently, Barbosa et al.[24] have suggested that the low frequency MHD waves observed in the magnetodisc of Jupiter are sufficiently intense to accelerate injected (or locally produced) ions to MeV energies. Presumably the MHD waves are maintained by free energy in the low energy plasma.

THE IO-INTERACTION

As Io moves through the corotating plasma it distorts the electric and magnetic field in its vicinity. This distortion is due to the current driven through the ionosphere or body of Io by the motional electric field seen in the frame of reference moving with Io (~ 0.1 V/m). This current must, of course, be closed by field aligned currents which are toward Io on the side facing Jupiter and away from Io on the side facing away from Jupiter. Before the discovery of the Io torus, it was believed that the current closes in the ionosphere of Jupiter.[25] It is now generally believed that the current system is closed by polarization currents in the front of an Alfven wave pulse wave pulse propagating along the magnetic flux tube.[26,27]

A simple picture of the interaction considers Io as a flat plate with the normal oriented parallel to the magnetic field (Figure 4). In that case the absorption of plasma and associated perturbations (sound waves) can be neglected. The plasma flow in the corotating frame satisfies

$$\frac{\partial^2 v}{\partial z^2} = \frac{1}{v_A^2(z)} \frac{\partial^2 v}{\partial t^2} \quad . \tag{6}$$

The boundary condition at $z = 0$ is

$$v(z = -\varepsilon) = v_< = v(z = +\varepsilon) = v_> \quad . \tag{7}$$

From Faraday's law and $\vec{E} + \vec{v} \times \vec{B} = 0$ we get

$$\frac{\partial v_>}{\partial z} - \frac{\partial v_<}{\partial z} = \frac{\mu_o}{B_o} \frac{\partial}{\partial t} I_{Io} = \frac{\mu_o}{B_o} \frac{\partial}{\partial t} \int_{-\varepsilon}^{\varepsilon} \Sigma_{Io} E_{Io} \, dz = 2 \frac{\mu_o}{B_o} \Sigma_{Io} \frac{\partial}{\partial t} E_{Io} \quad . \tag{8}$$

For a uniform medium we have

$$v(z,t) = v(v_A t \mp z) \tag{9}$$

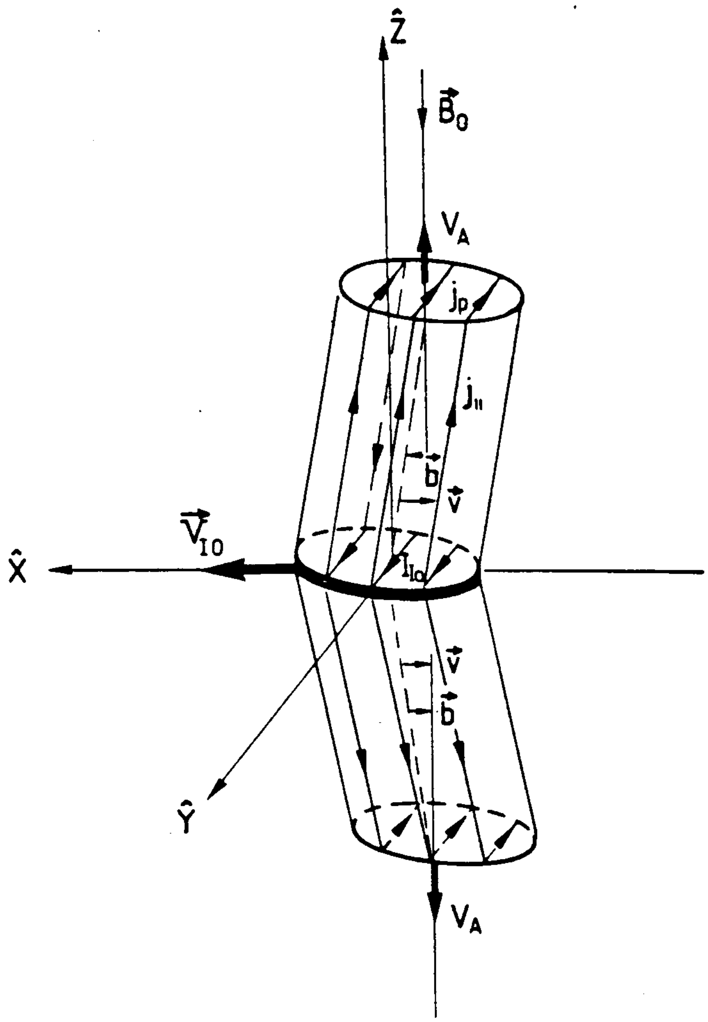

Fig. 4. A simple picture of the Io interaction. The field aligned currents are closed by a conductive current through Io and polarization currents in the leading fronts of the Alfven waves.

where the $\mp$ sign refers to waves propagating to positive and negative values of z, respectively. Writing

$$E_{Io} = B_o \,(v_{Io} - v(o)) \tag{10}$$

where $B_o = 0.02$ G is the background magnetic field at Io we see that Io launches two pulses propagating in opposite directions. The amplitude of each pulse is

$$A_v = v_{Io} \frac{\Sigma}{\Sigma + \Sigma_A} = k \; v_{Io} \tag{11}$$

where the Alfvén conductance Σ_A is

$$\Sigma_A = \frac{1}{\mu_o v_A} \quad . \tag{12}$$

The duration of each pulse (seen from a corotating frame) is

$$T = \frac{2R_{Io}}{v_{Io} - A_v} = \frac{2R_{Io}}{v_{Io}} \frac{1}{(1 - k)} = \frac{T_o}{(1 - k)} \quad . \tag{13}$$

The magnetic amplitude is

$$b(z,t) = \mp B_o \, v(z,t)/v_A \tag{14}$$

and the power flux

$$F = B_o^2 \, A_v^2/v_A \quad . \tag{15}$$

When v_A is not a constant the formulation becomes more complicated.[28]

For a thick atmosphere model of Io ($\int n \, dh > 10^{16}$ cm^{-2}) the Io conductance has been estimated as 12 mhos.[1] The Alfvén conductance is of the order of 4 mhos.[28] Thus $\Sigma/\Sigma_A \approx 3$ and the velocity amplitude is 3/4 v_{Io}. The duration of the pulse is 260 seconds. This is considerably less than the time it takes the Alfvén wave to propagate to the Jovian ionosphere and back (> 700 seconds).[29]

Thus the information about the conductive properties of the Jovian ionosphere cannot return to Io in time to influence the interaction. Before the discovery of the torus the Alfvén travel time was estimated as 60 seconds. In that case several reflections would occur before Io moves out of the flux tube considered and the ionosphere would control the current to a certain degree as discussed by Hill et al.[1]

It has been shown by Goertz[27] and Goldstein and Goertz[30] that there exists a parallel electric field at the leading and trailing edge of the Alfvén wave pulse generated by Io (Figure 5). This electric field will accelerate ambient electrons which carry the field aligned current between the leading and trailing edge of the pulse. The currents are closed by polarization currents. The energy of the current carrying electrons has been estimated as several keV at high latitudes.[30] These electrons appear as beams in velocity space and may be subject to several electrostatic instabilities which lead to the emission of radio waves into conical sheets by mode coupling.[30] There is also a possibility of an enlarged loss cone of electrons coming up from the ionosphere on the side of the flux tube facing Jupiter because the parallel electric field would decelerate them. This form of free energy is

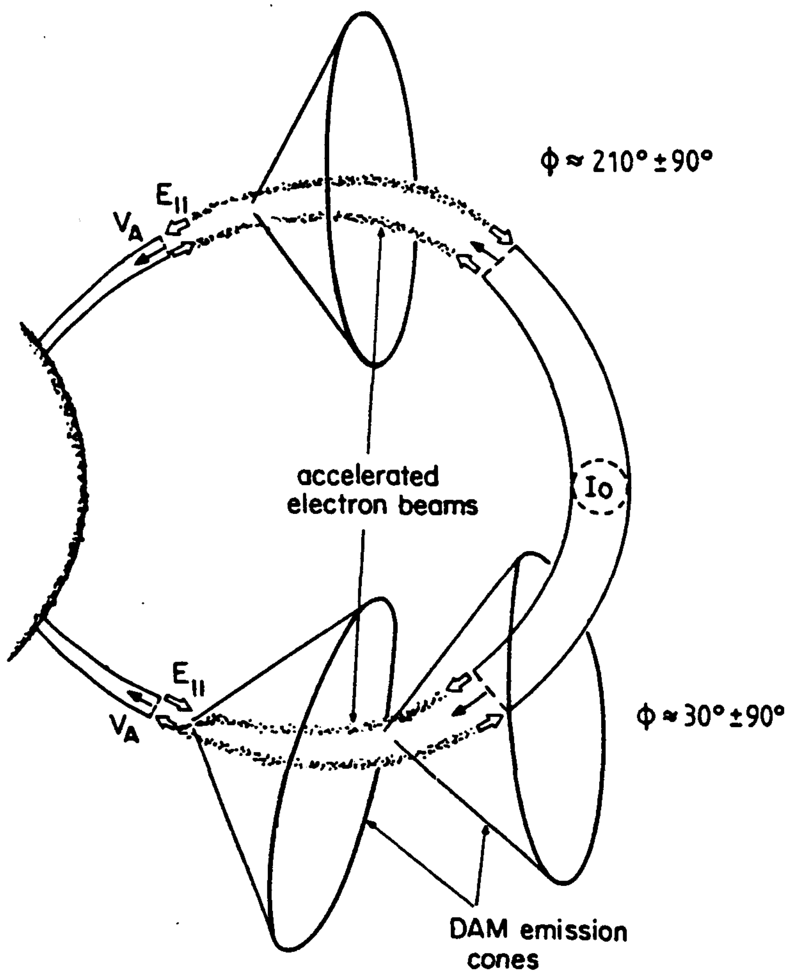

Fig. 5. A view of the Io-generated Alfvén wave pulse. At the leading and trailing edges parallel electric fields accelerate electrons which carry field aligned currents. These currents are confined to the region between the two edges of the pulse and may lead to the emission of radio waves into conical sheets.

suggested to drive the earth's auroral kilometric radiation (AKR). For a more detailed discussion see Goertz.[31]

In any case the conical sheets would provide for a natural explanation of the DAM arcs (Goertz[31]) as discussed by Gurnett and Goertz.[32] The multiplicity of arcs has a simple explanation also. The Alfvén waves will be reflected at the Jovian ionosphere and propagate back to the opposite hemisphere where they are again reflected, etc. At any time there is a pattern of Alfvén waves attached to and carried around by Io as shown in Figure 6. Thus at any time many closely spaced DAM sources may be active. Each source traces out an arc-like structure in the frequency-time diagram (Figure 7) as the pattern rotates with Io. Of course, the

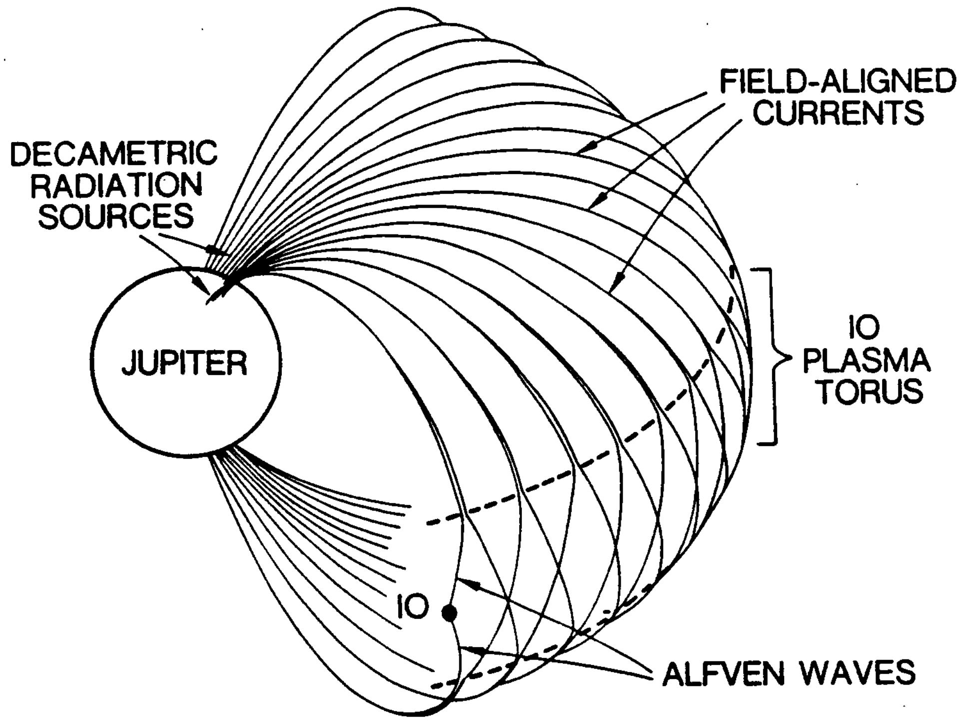

Fig. 6. The pattern of Alfvén waves associated with Io. The traces indicate the position of one edge (say the leading edge) of the Alfvén wave.[32]

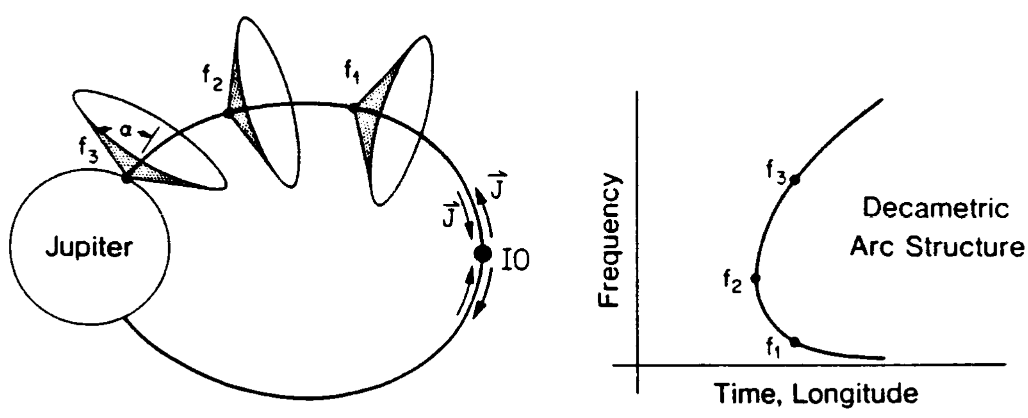

Fig. 7. The basic explanation of the DAM arcs. Radiation is detected only if one of the radiation cones passes over an observer. At any time there are, in general, two cones visible by an observer emitting at two different frequencies. These frequencies will vary as the observer rotates relative to the meridian along which the cones are emitted.

radio emission provides a damping for the Alfvén waves in addition to the collisional damping in the ionosphere. Gurnett and Goertz[32] estimate that about 50 reflections are needed to damp the waves significantly (mainly by collisional damping). Thus at any time 50 DAM sources may be active and the whole Alfven pattern may extend completely around Jupiter. However, this number depends on the ionospheric conductance which is poorly known. (For $\Sigma = 0.1$ mho only 10 reflections may occur.)

WAVE-PARTICLE INTERACTIONS

We have already mentioned the importance of wave-particle interactions several times. We now discuss the role of wave particle interactions for the maintenance of the auroral UV activity and the heating of the torus. Broadfoot et al.[33] have shown that the total radiated power from the polar regions which apparently map along field lines from the Io torus is 3×10^{12} W. The best estimates to account for this power requires (0.3 to 1.2) $\times 10^{14}$ W to be dissipated by energetic particle precipitation into the Jovian atmosphere.[34] The most liberal estimates for overall energy deposition of energetic electrons is less than 10^{13} W.[34] This falls short of the required input. Goertz[35] and Thorne[34] have thus suggested that energetic ions scattered into the atmosphere on field lines with $6 < L < 8$ are responsible for the UV emission. And, indeed, the flux of trapped ions with energies above 500 keV decreases significantly from $L = 8$ to $L = 6$. The observed deficit of ion-fluxes at $L = 6$ when compared with $L = 8$ above 500 keV corresponds to a loss of 3×10^{13} W. Extrapolating this to below 100 keV would be able to account for the 10^{14} W needed. No equivalent decrease of electron fluxes is seen. Thorne[34] also suggests that backscattered electrons (secondaries) are of fundamental importance for heating the Io plasma torus. Unfortunately, the ion-cyclotron waves which are most likely responsible for the scattering have not been measured. However, Thorne[34] has shown that the observed ion fluxes at $L = 8$ are large enough to cause rapid growth of ion cyclotron waves and strong pitch-angle diffusion. Gurnett and Goertz[36] on the other hand argue that energetic electrons produce electron cyclotron waves (whistlers) which mode convert into ion-cyclotron waves. They also show that pitch-angle diffusion by the anomalous gyroresonance between electron cyclotron waves and ions is quite strong and may be sufficient to explain the ion precipitation. In any case, the ultimate source of the UV power is the same as that responsible for the acceleration of ions in the outer magnetosphere.

SUMMARY

Various arguments suggest that the dissipation of Jupiter's rotational energy (6×10^{34}) is responsible for driving the diverse energetic phenomena such as auroral UV radiation, energetic particle acceleration and radio emissions. Rotational energy can be tapped by particle injection, magnetic pumping and field aligned electric fields (slippery clutch). We have pointed out that each mechanism requires field aligned currents coupling the outer magnetosphere to the Jovian ionosphere. Jupiter's magnetosphere is clearly less energetic than astrophysical magnetospheres, but more energetic than the earth's magnetosphere. Certain processes such as radial diffusion and wave particle interactions which occur near the earth also occur at Jupiter. Other processes which may be more important in astrophysical magnetosphere such as magnetic pumping, tapping of rotational energy occur at Jupiter, but are less important at the earth. Thus Jupiter is a kind of rosetta stone linking the well-studied magnetosphere of the earth with the inaccessible magnetospheres of astrophysical objects.

ACKNOWLEDGEMENTS

This work was supported by NASA grants NAGW-386, NSG-7632, NGL-16-001-043, and NSF grant ATM-811126.

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